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Numerical and experimental study of flame propagation and quenching of lean premixed turbulent low swirl flames at different Reynolds numbers

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ABSTRACT

This paper presents a joint experimental and large eddy simulation (LES) study of lean premixed low swirl stabilized methane/air flames at different Reynolds numbers (Re ~ 20,000–100,000). The aims are to investigate the sensitivity of the structures and dynamics of low swirl flames to the inflow boundary conditions and to evaluate the capability of an LES flamelet model in predicting the stabilization and local extinction of the flames. Chemiluminescence measurements are carried out for Re = 20,000–50,000 and further detailed oxygen concentration and temperature fields are measured using rotational coherent anti-Stokes Raman spectroscopy (RCARS) for Re = 20,000 and 30,000 along the centerline of the burner and at various radial positions at different heights above the burner. The data are used first for validation of the combustion LES model employed in the numerical simulations, and then the RCARS and LES results are used to delineate the effect of ambient air entrainment on the flame structure at various burner exit velocities. A three-scalar flamelet model based on a level-set G-equation shows excellent predictions of the lift-off positions and the structures of the flames, including quenching at the trailing edge of the flame. The results show that the flame lift-off height varies only slightly when the burner exit velocity is increased, which is consistent with a shear-layer flame stabilization mechanism reported previously. The volume of the flame decreases substantially with increasing burner exit velocity at relatively low Reynolds numbers, as a result of flame quenching at the trailing edge of the flame caused by entrainment of the ambient air into the fuel/air stream and the flame itself. At high Reynolds numbers the flame structures become fairly self-similar with the flame volume nearly independent of the Reynolds number.

1. Introduction

Lean premixed flames stabilized in swirling flows are widely used in gas turbine engines owing to the advantage of low emission of nitric oxides. A variant of the swirl stabilized premixed flame that has been studied recently in several groups [1–8] is the low swirl flame (LSF) originally developed by Cheng et al. [1–3]. Different from high swirl burners, low swirl burners give rise to only weak (or no) vortex breakdown and recirculation zones; the flame is therefore typically stabilized at a higher lift-off height from the burner nozzle, which can be helpful for preventing the flame from flashing back and overheating the burner. In addition to its other advantages, e.g., the low NOx and the low noise behavior, the low swirl flame burner provides a valuable validation rig for evaluating numerical simulation models for turbulent premixed flames. The LSF burner of Lund and Darmstadt [4,5] has been the focus of several modeling validation and flame-flow interaction studies [5,8–14], where three-component flow field and distributions of fuel and OH radicals have been studied experimentally. Numerically, studies have been performed using large eddy simulations (LES) based on level-set G-equation and flamelet assumption [5,9–14], and based on finite rate chemistry models [9].

A challenge of experimental and numerical studies of swirling premixed flames is the high sensitivity of the flow to the in-swirler flow, which demands a proper specification of the inflow boundary condition for numerical simulations that exclude the swirler geometry. Under low swirl conditions, there is no significant vortex breakdown in the flow field; the flow swirl at the burner exit

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results in a deceleration of the axial velocity downstream the burner, forming a low speed region where the flame can be stabilized. It has been shown recently that the deceleration of the axial velocity along the burner axis is rather different in the experiments made at different laboratories under the same flow conditions and with nearly identical copies of the burner [8]. The difference in the velocity field with these burners is likely due to the minor difference in the details of the swirler fabrication and the high sensitivity of flame structure to the in-swirler flow condition. In another study it was noticed that the fine flow structures generated in the swirler, which are usually not measured in experiments, can affect the lift-off position of the flame [10]. The high sensitivity of swirling flame to the inflow condition provides an opportunity to evaluate simulation models in capturing important flow physics in swirling flames.

An important feature of swirling flames operating at open atmospheric conditions is the quenching of the flame at downstream positions due to dilution and cooling by the ambient air. Previous numerical simulation models [5,9–14] show capability of qualitatively being able to capture the quenching of the flame at the trailing edge. However, no detailed analysis of the model performance has been reported owing to the lack of experimental data (under systematically varying flow conditions) for model evaluation. The need of providing reliable experimental data for evaluation of combustion models under challenging swirl flame conditions, including flame quenching, has motivated the present work.

In this paper a joint experimental and numerical study on low swirl premixed methane/air flames is presented. Special focus is on the characterization of the mixing field and flame structures of the Lund University low swirl flame at different burner exit velocities. By doing so, the sensitivity of the flame to the inflow condition can be evaluated. Large eddy simulations are performed under Reynolds number of 20,000 up to 100,000 conditions using a three-scalar flamelet model based on level-set G-equation for stratified premixed flames. Chemiluminescence measurements for four different burner exit velocities are conducted to qualitatively investigate the Reynolds number dependency of the flames. The temperature and relative oxygen mole fraction at various radial and axial positions above the burner exit plane are measured using rotational coherent anti-Stokes Raman spectroscopy (RCARS) at two burner exit velocity conditions.

Previously, 2D temperature data has been extracted using filtered Raman scattering (FRS) at the same experimental conditions [9]. Improved experimental temperature data can be expected in this work due to the better accuracy of RCARS as compared with the FRS technique. Also, while the FRS measurements covered a $\sim$1 cm high region around the highly fluctuating lowest flame front region, the new RCARS measurements map up the temperature field of the flames, up to 150 mm height above the burner (HAB). Additionally, along with the temperature data, the RCARS measurements also provide single shot statistics on relative O_2/N_2 concentration information. Previous publications have presented RCARS data for an axial scan of the Re = 20,000 flame [11] and extensive temperature data for the Re = 30,000 flame [12]. In this work we report the entire temperature field for the Re = 20,000 case, along with results for the Re = 30,000 case. The datasets at both conditions are compared and used to validate the LES results and to assist the analysis of flame structures at higher Reynolds numbers.

2. Experimental methods and operating conditions

The low swirl burner used in this investigation has been detailed previously [4,5]. The premixed methane/air-flames had an equivalence ratio of 0.62 and were operating at the atmospheric pressure for the Re = 20,000 up to Re = 100,000 conditions. The Reynolds number is defined based on the burner diameter, D = 50 mm, and the bulk flow velocity at the burner exit, U_c, i.e. $\mathrm{Re} = (D \cdot U_c)/\nu$, where ν is the kinematic viscosity of the fuel–air mixture at the burner exit. The mixture has a temperature of 298 K ($\nu = 15 \cdot 10^{-6}\ \mathrm{m^2/s}$), which passes the burner nozzle both through a central perforated plate and through an outer annular swirler that generates the swirling motion of the flow. The swirl number, based on the ratio of the angular momentum flux to the axial momentum flux, is 0.55 [4,5]. The gas mixture is surrounded by a large co-flow of air, which is fed at a low speed of 0.35 m/s. Due to limitations in the experimental flow system, experimental measurements at Re > 30,000 could not be performed in the present RCARS study.

The rotational CARS setup used in this experiment has been presented in our previous works [11,12] and only a short overview will be given here. A coherent CARS signal beam was generated by focusing and spatially overlapping the beams from an Nd:YAG laser and a dye laser in a so-called planar BOXCARS phase-matching scheme. The resulting signal beam carried information about the conditions in the $\sim 1.3 \times 0.1 \times 0.1\ \mathrm{mm^3}$ probe volume (defined as the volume contributing to 90% of the signal) and was spectrally dispersed and recorded using a spectrometer and a CCD camera. In dual broadband RCARS the entire rotational population of the molecules is probed in a single laser shot and temperature and relative mole fractions of oxygen can be extracted simultaneously by studying the relative peak intensities. The relative mole fraction of oxygen is the ratio of the oxygen mole fraction to the sum of oxygen and nitrogen mole fractions. In practice, this is done by generating theoretical spectra in which temperature and concentration, along with other experimental parameters, are floated to numerically minimize the residual between theoretical and experimental spectra.

Collecting CARS data from the highly turbulent low swirl burner flame proved to be challenging due, in part, to highly fluctuating CARS signal levels. This was addressed by spreading the CARS signal over more pixels on the CCD chip according to a procedure described in [11], and thereby increasing the dynamic range of the CCD camera. This procedure reduced the signal-to-noise ratio of the obtained data to some extent, but still the temperature precision was maintained throughout the temperature range of the flame (300–1700 K). Due to the turbulent nature of the flame a short probe volume was desirable to minimize spatial averaging effects. The laser beams used in the BOXCARS scheme were therefore placed in a geometrical arrangement with a crossing angle approximately twice as large as in our standard procedure [11], thereby shortening the length of the probe volume. Spatial averaging effects could still be observed along with beam steering effects due to sharp temperature gradients in the flame [11]. However, these spectra comprised only a small fraction of the collected data. Further measurement details and discussions on the applicability of the DB-RCARS technique for turbulent flames have been detailed in [11].

Temperature and relative O_2 mole fraction data for the two cases were measured at various locations by translating the low swirl burner vertically and horizontally using two motorized stages, while doing CARS measurement at a point fixed in space. One vertical and seven horizontal scans at different heights were made. The measurement positions in these scans were chosen to cover the dynamics of the flame in terms of the temperature and the O_2 concentration. The measurements at each position consisted of 1000 single shot spectra. Recent calibration measurements of N_2 rotational CARS thermometry in the range 300–800 K show uncertainties less than 1% of the real temperature, and single-shot relative standard deviation of 4–5% in pure N_2 [15]. Since this is a real flame